SOME CHARACTERISTICS OF AN *OSCILLATORIA*-DOMINATED METALIMNETIC PHYTOPLANKTON COMMUNITY[1]

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ABSTRACT

Crystal Lake, located in Crawford County, Pennsylvania, is a small dimictic lake which during summer stratification contains a large population of *Oscillatoria agardhii* var. *isothrix* Skuja in the metalimnetic region. Carbon fixation measurements indicate that this *Oscillatoria*-dominated community is capable of relatively rapid rates of photosynthesis at low levels of illumination.

Analyses of dissolved oxygen, carbon dioxide, phosphate, calcium, iron, manganese, phosphorus, zinc, and chlorophyll *a* were made on water and seston samples from a vertical water column near the center of the lake. The results of some of these analyses indicate that increased availability of trace nutrients may be involved in the occurrence of the *Oscillatoria*-dominated community.

INTRODUCTION

As Findenegg (1965) has pointed out, primary production in lakes generally takes place in nonhomogeneous layers. During the summer months some lakes become thermally stratified. At this time there may be essentially two phytoplankton communities present, the first in the epilimnetic region and the the second in the metalimnetic region. In many of these well-stratified lakes the metalimnetic community may be dominated by members of the blue-green algae, particularly species of *Oscillatoria* (Eberly, 1959, 1964a, b; Findenegg, 1965).

During the later summer of 1966, a carbon fixation maximum was observed in the metalimnion of a small lake, Crystal Lake, in northwestern Pennsylvania. This lake is a dimictic lake which during summer stratification contains a large population of *Oscillatoria agardhii* var. *isothrix* Skuja at and below the 1-percent level of incident illumination; this has been considered to be the lower boundary of the euphotic zone.

The purpose of this study was to investigate the relative importance of the *Oscillatoria*-dominated community to the productivity of Crystal Lake during the summer months and to determine the importance of the various factors involved in the occurrence of the community.

DESCRIPTION OF THE STUDY AREA

Crystal Lake is located in Crawford County, Pennsylvania, U.S.A., adjacent to the village of Hartstown. Crystal Lake is the middle and largest lake in a chain of three which, according to Grimm (1952), are the remnants of the extensive Pymatuning Lake formed following Wisconsinan glaciation (Leggette, 1957). The smallest lake, Dollar Lake, lies to the north and drains into Crystal Lake. Crystal Lake drains into Lower Lake, which is the second largest of the three and lies south of Crystal Lake. Crystal Lake and Lower Lake are separated by a small quaking bog (Sutton, 1928; Grimm, 1952). The three lakes are part of the Shenango River drainage basin.

Crystal Lake is a kettlehole lake, ovate in shape and elongated in a general north-south direction. The basin slopes steeply toward the center, where the maximum depth is seven meters. Maximum length of the lake is 525 meters and maximum width is 370 meters; surface area is approximately 13 hectares.

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METHODS AND PROCEDURES

During August 1966 and June, July, and August 1967, water samples were collected from different depths of a vertical water column near the center of the lake. Temperature measurements were made with a Whitney underwater thermometer at each depth sampled. The water samples were taken immediately to the laboratory, where analyses for dissolved oxygen, dissolved carbon dioxide, pH, alkalinity, and chlorophyll *a* were made. Standard methods (American Public Health Association *et al.*, 1965) were followed in most of these analyses; pigments were determined spectrophotometrically using the methods of Richards and Thompson (1952), but the quantities of the separate fractions were calculated by the equations of Parsons and Strickland (1963).

The water samples were filtered through Millipore HA (0.45 micron) membrane filters. The filtered water was then frozen in plastic bags and stored for future chemical analyses. The filters, bearing the seston samples, were placed in glass vials, dried in a desiccator over drierite for 48 hours, and stored for future analyses. The seston samples were digested just prior to analysis by a modification of the method described by Johnson and Ulrich (1959).

Phosphate concentrations were measured colorimetrically on thawed water samples and on the digested seston material using the stannous chloride method for orthophosphate (American Public Health Association, *et al.*, 1965). Analyses on water and seston samples for calcium, iron, manganese, nickel, and zinc were carried out using a Perkin-Elmer Model 290 atomic absorption spectrophotometer. The atomic absorption spectrophotometric methods used were those outlined by Slavin (1966).

Plankton samples for determining cell numbers were preserved with Lugol's solution and stored in glass vials. Plankton from 10 ml of lake water from each sampling depth were settled in Zeiss cylindrical plankton chambers for examination (Utermohl, 1936). Identification of the algae present and quantitative estimates of numbers of each algal taxon of the phytoplankton communities at each depth were made with the aid of a Nikon Model M inverted microscope equipped with phase optics.

Measurements of carbon fixation rates were carried out using the carbon-14 method. Ampoules containing 5 microcuries of carbon-14-labeled sodium bicarbonate were added to 125-ml bottles containing the lake water collected from each sampling depth. "Dark" bottles covered with black plastic tape were used to measure carbon fixation by nonphotosynthetic processes. Light and dark bottles were fastened to a chain suspended from a surface float, and the inoculated water samples were resuspended in the lake at the depths from which they were collected. Incubation periods of 3 to 5 hours were used to measure carbon fixation from approximately dawn to dusk. The amount of radioactive carbon fixed was determined by counting with a Nuclear-Chicago scaler and gas flow detector system. At the beginning of each interval total carbon available was calculated from the alkalinity, pH, and temperature values for each depth (Saunders, Trama, and Bachmann, 1962).

Studies were carried out to obtain additional information about certain aspects of the metalimnetic community of Crystal Lake and the *Oscillatoria* species from the metalimnetic communities of other lakes. Experiments with the metalimnetic community of Crystal Lake were performed under laboratory conditions with water collected from the 5.0-meter depth. Water from the lake was placed in 125-ml pyrex bottles which were then incubated horizontally on an Eberbach shaker inside a Shearer Model CEL 25–7HL environment chamber at 10°, 15°, 20°, and 25°C.

The lake-water cultures were incubated for 1 hour before inoculation with radiocarbon to permit equilibration to the temperature and light conditions. Following equilibration, the bottles were inoculated with 0.5 microcurie of carbon-14-labeled sodium bicarbonate. The bottles were then incubated for 3 hours on the shaker in the environment chamber. Dark samples were also run for each experimental condition to measure fixation under dark conditions.

Three levels of radiant energy were maintained by using various numbers of layers of aluminum-wire screen as light attenuators (McAllister and Strickland, 1961). The highest level, 5.1 x 10^4 ergs/cm^2-sec, was greater than the highest

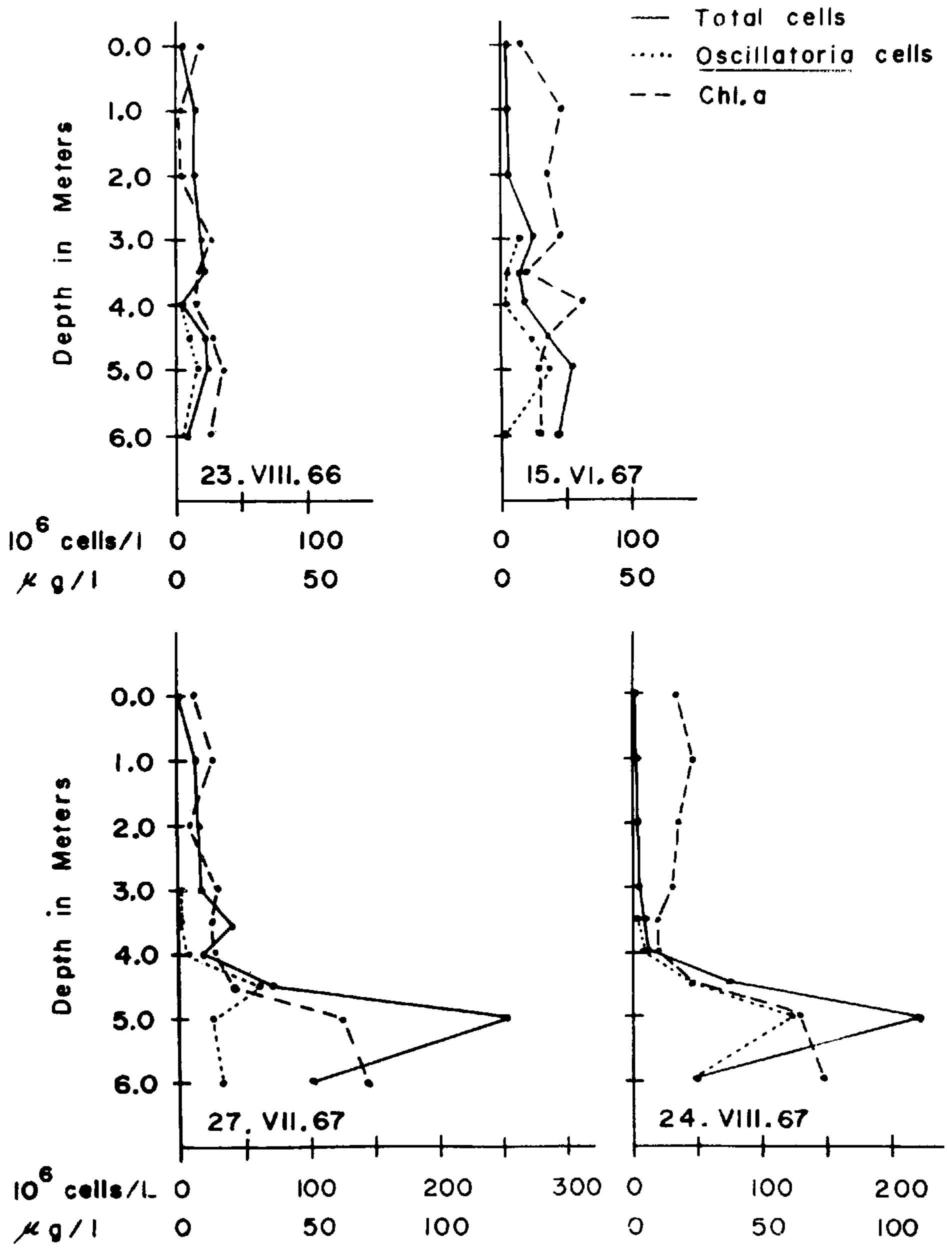

FIGURE 1. Crystal Lake. Vertical distribution patterns of phytoplankton cells and chlorophyll *a* for 23 August 1966; 15 June, 27 July, and 24 August 1967.

level measured at the 5.0-meter depth in the lake at noon on a bright sunny day. The middle level, 3.5×10^4 ergs/cm^2-sec, was approximately the level of radiant energy reaching the 5.0-meter depth at noon on a bright sunny day. The lowest level of light intensity used was 2.9×10^4 ergs/cm^2-sec, which was lower than the level of radiant energy reaching the 5.0-meter depth at noon on a bright sunny day.

RESULTS

Pertinent data are summarized in graphic form in figures 1 to 4 and tables 1 to 4. These figures were prepared using actual values obtained and with no deletion of nonconforming results. No attempt was made to draw curves which best fit the majority of points. Scales were selected to make the minor variations appear slight.

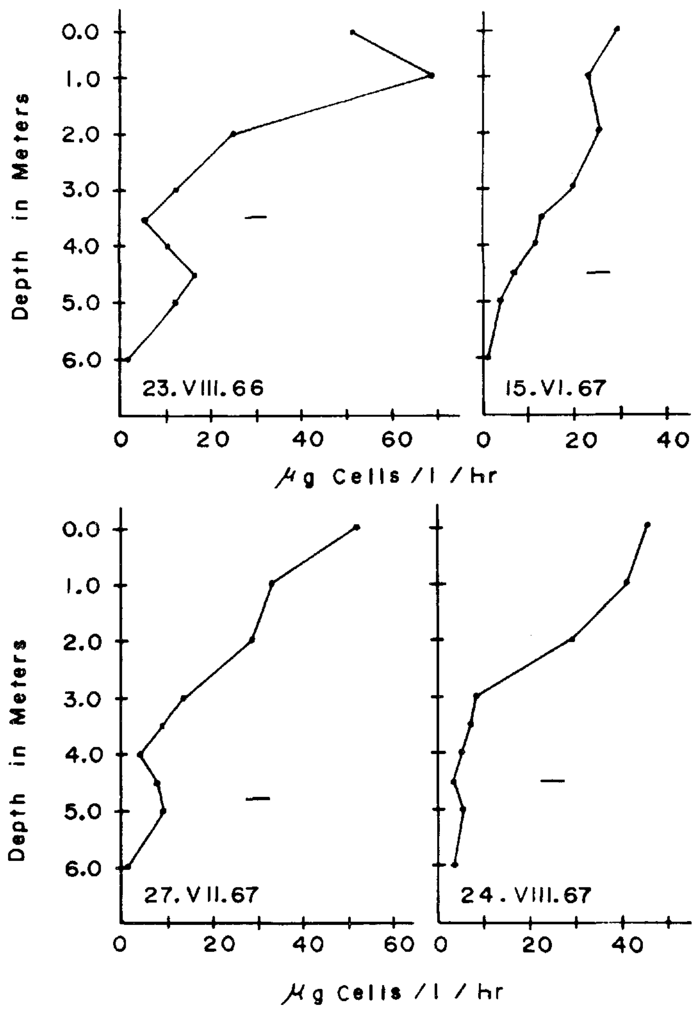

FIGURE 2. Crystal Lake. Vertical patterns of carbon fixation rates for 23 August 1966; 15 June, 27 July, and 24 August 1967. Horizontal line indicates 1-percent level of incident illumination.

Field Studies—Biological

The vertical distribution patterns of chlorophyll *a* for August 1966 and June, July, and August 1967 are presented in figure 1. During summer stratification, high concentrations of chlorophyll *a* were found in and below the metalimnion. The plankton community was dominated by *Oscillatoria agardhii* var. *isothrix*, with species of *Selenastrum*, *Merismopedia*, *Anabaena*, *Melosira*, *Chlamydomonas*, *Trachelomonas*, *Synura*, *Crucigenia*, and *Oocystis* present in decreasing amounts in the order given.

The vertical distributions of phytoplankton, as measured by direct cell counts or by counting colonies of colonial forms and converting to cell counts using an appropriate conversion factor, are also presented in figure 1. These curves rep-

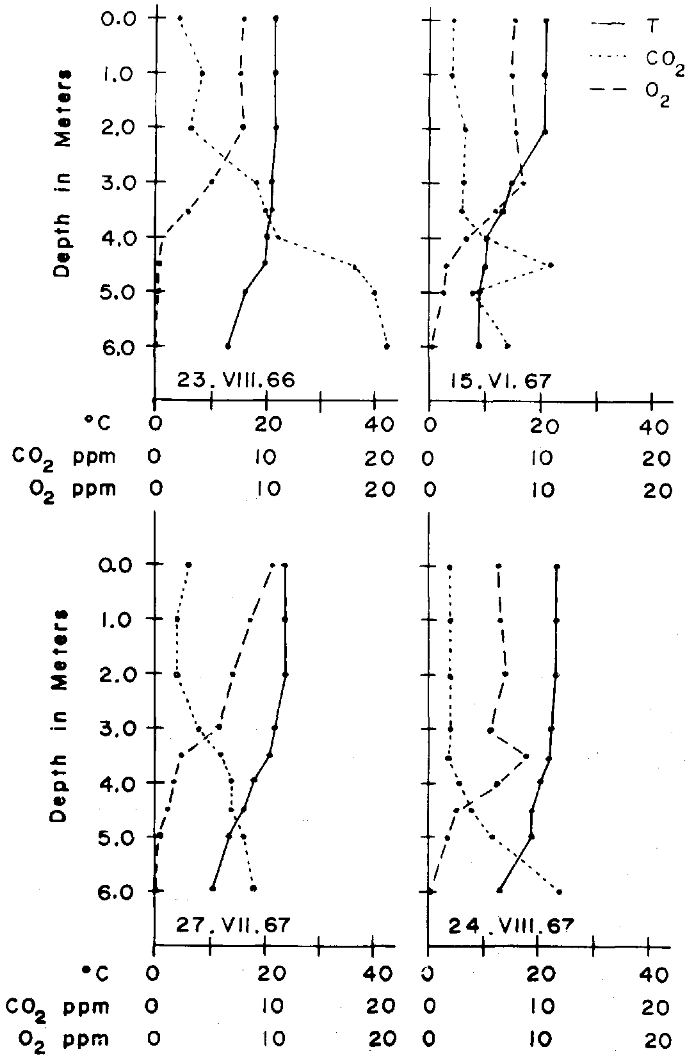

FIGURE 3. Crystal Lake. Vertical distribution patterns of temperature (°C), dissolved oxygen (ppm), and dissolved carbon dioxide (ppm) for 23 August 1966; 15 June, 27 July, and 24 August 1967.

resent the total for all species; in addition, the cell counts for *Oscillatoria* are presented separately to illustrate their abundance within the community. With respect to the standing crop of phytoplankton it is evident that the *Oscillatoria*-dominated community is an important part of the phytoplankton community of Crystal Lake during summer stratification.

The vertical patterns of the carbon fixation rates are shown in figure 2. From these data it can be seen that the highest rate of fixation of the 23 August 1966 measurements occurred at the 1.0-meter depth. An increase in the rate of carbon fixation corresponding with the chlorophyll and standing crop maxima occurred also in the metalimnetic region on this date. No increase in dissolved oxygen (figure 3) occurred in the metalimnetic region in association with the carbon fixation maximum. The carbon fixed per square meter by the metalimnetic community was about 18 percent of the total carbon fixed per square meter through the entire water column.

In the 15 June 1967 study there was no observed increase in the carbon fixation rates in the levels of the lake where the *Oscillatoria*-dominated community had become established. In the 27 July 1967 study an increase in carbon fixation rates was observed in the *Oscillatoria* region of the lake relative to the strata just above it in the vertical water column. In the 24 August 1967 measurements there was only a minor increase, relative to the upper strata, in carbon fixation rates in the *Oscillatoria* region of the lake. An oxygen maximum (fig. 3) was evident at depths just above the *Oscillatoria*-dominated communities during the August 1967 study.

Field Studies—Physical and Chemical

Vertical distribution patterns of temperature, dissolved oxygen, and dissolved carbon dioxide during the summer of 1967 are presented in figure 3. The development of the metalimnion began about the middle of May and the summer stratification was established by mid-June. The thickness of the metalimnion varied from 2 to 3 meters during the summer. Throughout the summer the metalimnion occurred at increasingly greater depths until, during late August or September, it reached the lowest level (4–6 meters). Fall turnover generally occurred in late September or early October; however, in 1967 turnover occurred in early September.

As the lake became thermally stratified the oxygen concentrations at the lower levels of the lake diminished, and at times anaerobic conditions existed in the hypolimnion. Increased concentrations of dissolved oxygen were observed at various depths of the lake during summer stratification. These increases usually corresponded with the highest concentrations of organisms as indicated by the chlorophyll measurements and cell counts.

The carbon dioxide concentration curves were approximately the inverse of the oxygen concentration curves. The highest carbon dioxide concentrations in the hypolimnion were observed when pH values were low.

The results of the analyses of calcium, iron, manganese, phosphate, and zinc are presented in tables 1 to 4. At no time was dissolved iron or manganese observed in the more highly oxygenated levels of the water column, and only on one occasion were detectable amounts of dissolved iron observed in the hypolimnion during summer stratification. Detectable amounts of dissolved manganese were usually present in the hypolimnion during summer stratification. The distribution of calcium in the water column exhibited no pronounced stratification. Measurable amounts of zinc were present throughout the period of the study. The distribution of zinc showed no strong stratification pattern in either the dissolved or particulate forms. Dissolved phosphate was detected throughout the study. The particulate phosphate concentrations in most instances showed less variation throughout the water column than did the dissolved phosphate. Both dissolved phosphate and particulate phosphate were in higher concentration in the hypolimnetic region.

TABLE 1

Results of chemical analyses from samples taken at nine depths through the vertical water column in Crystal Lake. August 1966

Depth (m)	Calcium (mg/l)		Iron (mg/l)		Manganese (mg/l)		Phosphate (mg/l)		Zinc (mg/l)	
	Soluble	Seston	Soluble	Seston	Soluble	Seston	Soluble	Seston	Soluble	Seston
0.0	9.0	1.3	n.d*	0.57	n.d.	0.06	0.04	0.01	0.25	0.04
1.0	9.0	2.1	n.d.	0.09	n.d.	0.06	0.03	0.05	0.13	0.06
2.0	8.0	1.7	n.d.	0.08	n.d.	0.05	0.06	0.03	0.18	0.06
3.0	8.0	2.3	n.d.	0.08	n.d.	0.04	0.03	0.03	0.31	0.06
3.5	8.0	1.1	n.d.	0.10	0.05	0.05	0.04	0.01	0.25	0.05
4.0	9.0	2.8	n.d.	0.08	0.10	0.13	0.07	0.04	0.13	0.05
4.5	10.0	0.7	n.d.	0.12	0.40	0.09	0.07	0.06	0.18	0.03
5.0	10.0	4.5	n.d.	0.25	0.40	0.53	0.04	0.07	0.25	0.09
6.0	13.0	11.8	n.d.	0.69	0.85	0.61	0.06	0.09	0.25	0.16

*Not detectable.

TABLE 2

Results of chemical analyses from samples taken at nine depths through the vertical water column in Crystal Lake. June 1967

Depth (m)	Calcium (mg/l)		Iron (mg/l)		Manganese (mg/l)		Phosphate (mg/l)		Zinc (mg/l)	
	Soluble	Seston	Soluble	Seston	Soluble	Seston	Soluble	Seston	Soluble	Seston
0.0	8.3	0.1	n.d.*	0.04	n.d.	0.02	0.03	0.01	0.20	0.05
1.0	7.5	1.6	n.d.	0.06	n.d.	0.01	0.07	0.02	0.01	0.05
2.0	7.3	1.5	n.d.	0.06	n.d.	0.02	0.07	0.02	0.10	0.05
3.0	6.0	1.7	n.d.	0.07	n.d.	0.03	0.04	0.04	0.10	0.05
3.5	7.5	1.3	n.d.	0.07	n.d.	0.05	0.11	0.06	0.07	0.04
4.0	6.3	2.6	1.43	0.13	n.d.	0.11	0.12	0.06	0.12	0.08
4.5	7.3	2.1	0.71	0.16	0.02	0.16	0.39	0.07	0.12	0.07
5.0	7.5	2.5	0.86	0.14	0.06	0.20	0.15	0.07	0.17	0.09
6.0	9.3	3.2	0.23	0.50	0.08	0.40	0.09	0.07	0.22	0.01

*Not detectable.

TABLE 3

Results of chemical analyses from samples taken at nine depths through the vertical water column in Crystal Lake. July 1967

Depth (m)	Calcium (mg/l)		Iron (mg/l)		Manganese (mg/l)		Phosphate (mg/l)†		Zinc (mg/l)	
	Soluble	Seston	Soluble	Seston	Soluble	Seston	Soluble	Seston	Soluble	Seston
0.0	11.3	0.9	n.d.*	0.06	n.d.	0.02			0.13	0.04
1.0	11.4	0.4	n.d.	0.06	n.d.	0.02			0.13	0.04
2.0	11.2	0.4	n.d.	0.04	n.d.	0.01			0.22	0.07
3.0	12.5	0.6	n.d.	0.11	n.d.	0.03			0.12	0.10
3.5	12.3	0.9	n.d.	0.08	n.d.	0.03			0.11	0.05
4.0	11.6	1.1	n.d.	0.13	n.d.	0.12			0.05	0.06
4.5	12.4	0.9	n.d.	0.13	0.40	0.14			0.20	0.08
5.0	13.6	0.7	n.d.	0.24	1.40	0.22			0.16	0.04
6.0	13.3	1.8	n.d.	0.64	1.30	0.54			0.15	0.16

*Not detectable.
†Phosphate not measured.

TABLE 4

Results of chemical analyses from samples taken at nine depths through the vertical water column in Crystal Lake. August 1967

Depth (m)	Calcium (mg/l)		Iron (mg/l)		Manganese (mg/l)		Phosphate (mg/l)		Zinc (mg/l)	
	Soluble	Seston	Soluble	Seston	Soluble	Seston	Soluble	Seston	Soluble	Seston
0.0	13.6	0.04	n.d.*	0.59	n.d.	0.08	0.09	0.01	0.11	0.04
1.0	14.0	0.14	n.d.	0.04	n.d.	0.03	0.03	0.04	0.21	0.02
2.0	14.3	0.02	n.d.	0.05	n.d.	0.04	0.03	0.04	0.08	0.04
3.0	14.6	0.05	n.d.	0.08	n.d.	0.05	0.07	0.05	0.18	0.03
3.5	14.6	0.05	n.d.	0.06	n.d.	0.05	0.04	0.04	0.17	0.04
4.0	14.1	0.05	n.d.	0.10	0.10	0.04	0.06	0.03	0.17	0.03
4.5	13.6	0.08	n.d.	0.12	0.40	0.02	0.07	0.02	0.25	0.03
5.0	13.2	0.24	n.d.	0.16	0.90	0.02	0.09	0.25	0.17	0.03
6.0	16.3	0.28	n.d.	0.67	3.30	0.03	0.19	0.24	0.35	0.08

*Not detectable.

Laboratory Studies

Rates of carbon fixation in water samples from the 5.0-meter depth of Crystal Lake were measured in the laboratory under a combination of three different light intensities and at four different temperatures (fig. 4). From these data it can be seen that the highest rate of fixation occurred at 15°C and at a radiant energy level of 3.5 x 10^4 ergs/cm^2-sec. The temperature of the lake water at the 5.0-meter level at the time of sampling was 15.4°C and the light intensity reaching this

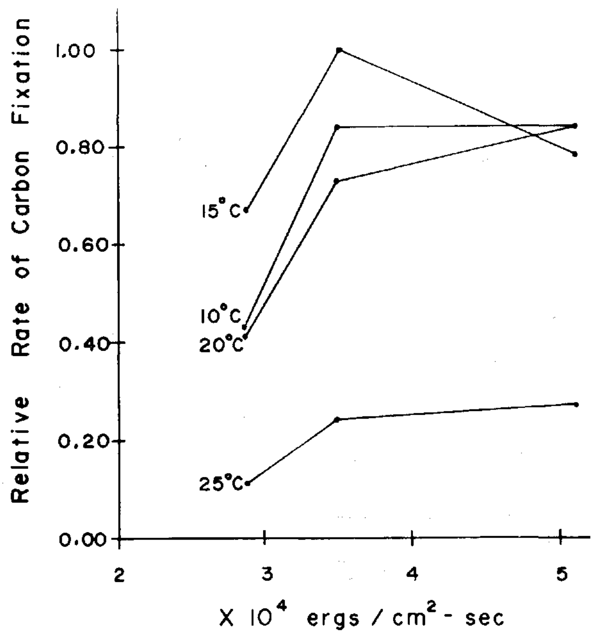

FIGURE 4. Relative rates of photosynthetic carbon fixation under laboratory conditions by the *Oscillatoria*-dominated phytoplankton community from the 5-meter depth of Crystal Lake during late August 1967. At this time the community consisted of 60 percent *Oscillatoria*. The results presented represent the average of six replicates.

level at noon on a sunny day was 3.5 x 10^4 ergs/cm^2-sec. The actual maximum rate of fixation measured in the environmental chamber was 1.1 μg carbon/liter/hr. The value obtained *in situ* one week before was 1.3 μg carbon/liter/hr. The number of cells per liter was essentially the same in both samples. On the basis of the results of these experiments, it was assumed that the lake conditions affecting carbon fixation were reasonably simulated in the laboratory.

DISCUSSION

As Hutchinson (1957) has pointed out, lakes harbor a series of very complex physiochemical and biological systems, each of which has its own characteristics and yet also has much in common with others. The morphometric characteristics of lake basins are considered to be among the dominant characteristics affecting lakes. The depth and area of the lake affect the temperature stratification pattern, which in turn influences the chemical and biological components of the system.

Crystal Lake is a relatively small lake with a steeply sloping basin and has a small fetch. These characteristics are considered necessary for stable stratification of *Oscillatoria* to occur (Eberly, 1959, 1964a; Ruttner, 1963, Findenegg, 1964, 1965).

Iron and manganese are known requirements for algal growth (Hutchinson, 1957; Goldman, 1965). These elements are quite similar in their behavior in natural waters, especially with regard to interaction with the phosphorus cycle. Under oxygenated conditions both iron and manganese are precipitated rapidly in the form of phosphates unless natural chelating agents are present (Lee, 1962; Goldman, 1965). In this study iron in solution was observed on only one occasion; this was in the hypolimnion during summer stratification and under near-anaerobic conditions. Soluble manganese was observed in the hypolimnion throughout the period of summer stratification. Particulate iron was observed throughout the vertical water column during the sampling period. As Hutchinson (1957) has stated, ferric hydroxides are often formed in natural waters under aerobic conditions. These compounds are flocculent precipitates which remain suspended in the water column and may act as a source of iron for the algae.

Eberly (1966) has found in his survey of lakes throughout the world that *Oscillatoria agardhii* var. *isothrix* usually appears as a dominant in mixed communities rather than as a "bloom" organism. In the present study also, the *Oscillatoria* community was observed to be dominated by *Oscillatoria agardhii* var. *isothrix*, with several other species present during summer stratification.

The ability of *Oscillatoria* species to sustain themselves physiologically has been attributed to a multiplicity of factors. One factor is the availability of nutrients to organisms in the metalimnion. During summer stratification in Crystal Lake the epilimnion became relatively depleted of nutrients such as iron and manganese. During this period of stratification iron, manganese, and phosphate were more abundant in and below the metalimnetic region. Eberly (1964a, b) and Findenegg (1965) have reported similar results, and they feel that organisms capable of maintaining themselves in the metalimnetic region would have the advantage of increased levels of nutrients. The concentration of nutrients in and below the metalimnion in Crystal Lake is one of the factors contributing to the size of the *Oscillatoria* community.

Of significance was the observation of increased carbon fixation rates in the metalimnetic region, which is often below the 1-percent level of incident illumination, as has also been reported by Eberly (1959, 1964a, b), English (1962), and Findenegg (1964, 1965). In most instances, oxygen maxima have been observed in conjunction with these communities. This has not always been the case in the present study, during which increased rates of carbon fixation were observed at times when there was no increase in the oxygen concentration of the water at these depths. In other instances, increases in the carbon fixation rates and oxygen concentration have been observed.

Findenegg (1965) has observed that in lakes with large populations of *Oscillatoria*, relatively small amounts of organic production are associated with these populations. In August 1967 the highest measured rate of fixation (37.0 mg $C/10^{10}$ cells/hr) in Crystal Lake occurred at the 2.0-meter depth. This was more than 600 times the rate of fixation (0.06 mg $C/10^{10}$ cells/hr) by the *Oscillatoria*-dominated community at 5.0 meters. These data suggest that the metalimnetic organisms were much less demanding in their energy requirements or that some other energy-yielding pathways might be supplementing their demands.

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